Polarized Solid Targets
requirements and operation

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Polarized Targets are "graded" on four criteria

1. Maximum polarization
   "Can't you make it higher?"
2. Speed of polarization
   "How much longer will this take?"
3. Polarization resistance to intense beams
   "Can we ask for more beam?"
4. Ratio of polarized to unpolarized material
   "What's all this junk?"

Dilution Factor, $f = \dfrac{\#\text{ of polarizable nuclei}}{\text{total }\#\text{ of nuclei in target}}$

Brute Force Polarization

Utilizes equilibrium polarization of nuclei at:

High Field
Low Temperature

Dynamic Nuclear Polarization

Microwaves transfer electron polarization to nuclear spins at:

Moderate Field,
Moderate Temperature

Continuously Polarized (Brute Force)

☹ Low Acceptance

☹ Low Luminosity

Frozen Spin

☺ High Acceptance

☹ Low Luminosity

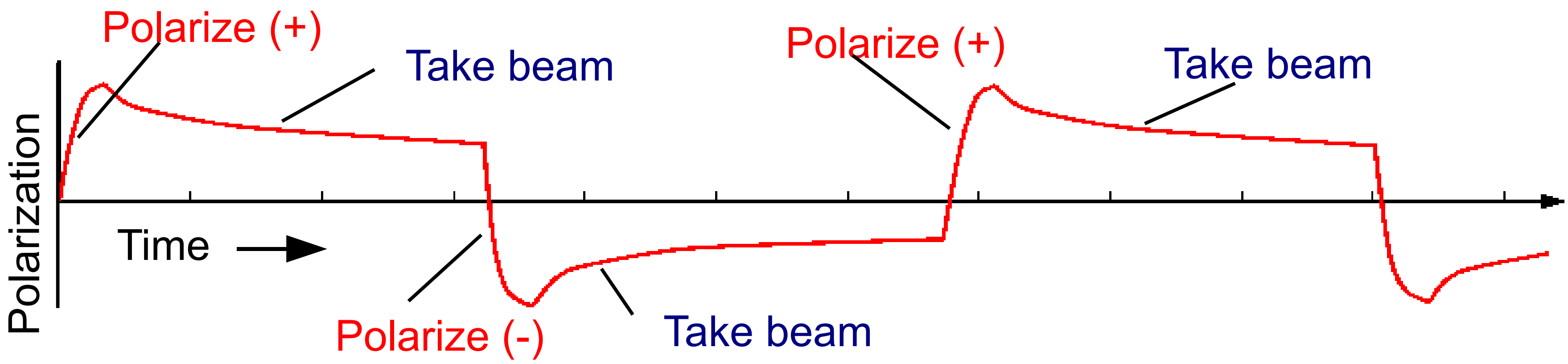
Continuously Polarized (DNP)

☹ Low Acceptance

☺ High Luminosity

Frozen Spin Target

- Polarize target material (e.g. via DNP at 5T and 0.3K)
- After optimum polarization is obtained, turn off microwaves, and magnet
- Use a 2nd magnet (~0.5 T) and very low temperatures (~ 50 mK) to "freeze" the polarization
- Polarization will decay exponentially with a spin-lattice time constant T_1 of (hopefully) several days



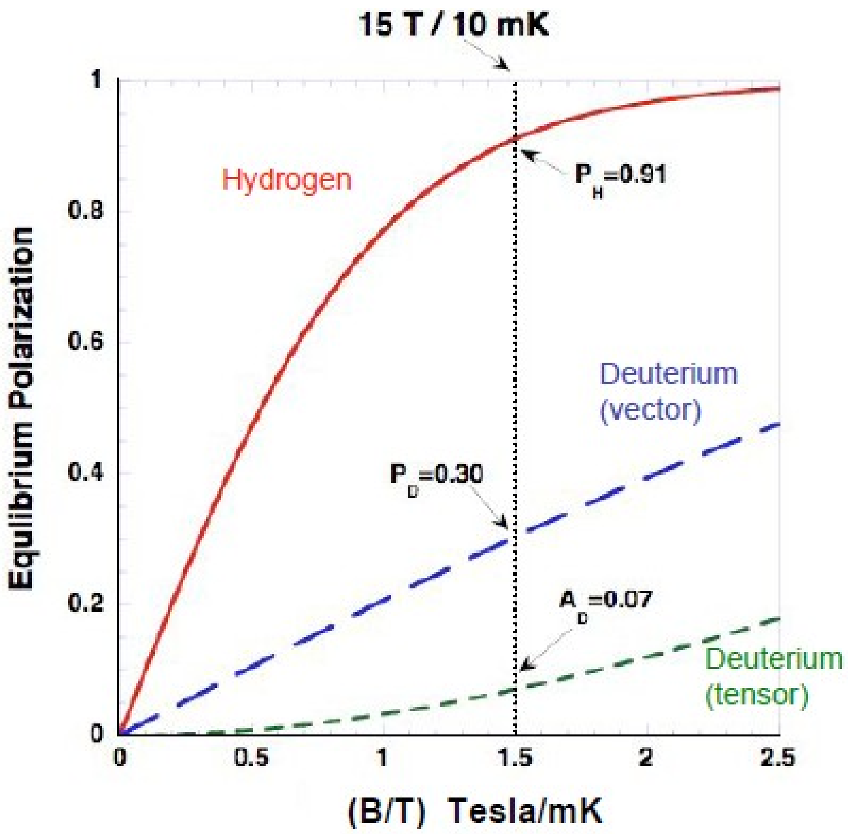
Brute Force Polarization

Utilizes the equilibrium polarization of the nuclear spin states achieved at a very low temperature and high magnetic field.

Spin 1/2 $\longrightarrow$ $P = \tanh\left(\frac{\vec{\mu}\cdot\vec{B}}{kT}\right)$

Advantage:
- Works for almost any material
- Easy to explain

Disadvantages:
- Requires very large magnet
- Low temperatures mean low luminosity
- Polarization can take a very long time (characterized by spin-lattice time, T_1



Dynamic Nuclear Polarization

- Invented in 1960's, a "better" way to polarize solid targets

- Advantages of DNP
  - Higher polarization (proton > 90%, deuteron > 70%)
  - Faster polarization (a few hours)
  - More moderate Field/Temperature requirements
  - Higher luminosity (up ~ 5×10^{35} cm^{-2} s^{-1})

- Disadvantages of DNP
  - Limited choice of target materials
    All have a dilution factor $f < 50\%$.

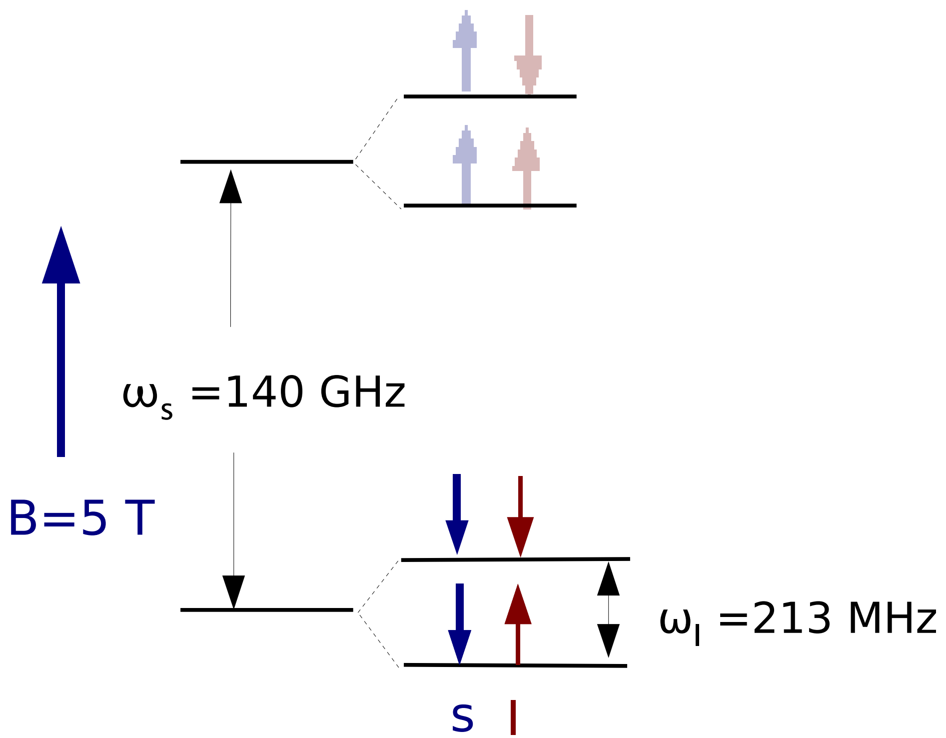
Dynamic Nuclear Polarization

- Implant target material with paramagnetic atoms or molecules.
  ~ 10^{19} spins/cc via irradiation or chemical doping
- Polarize the paramagnets via brute force at "modest" B & T
  ~ 90 – 100 %
- Use microwaves to "transfer" electron polarization to nearby nuclei
  - Overhauser Effect
  - Solid Effect
  - Cross Effect
  - Thermal Mixing
- Nuclear polarization spreads through material via Spin Diffusion
- Works at *B/T* conditions where
  - T_1(electron) is short (msec)
  - T_1(nucleus) is long (minutes)

SLAC style	$B = 5$ Tesla $T = 1$ Kelvin
Higher Luminosity	

CERN style	$B = 2.5$ Tesla $T = 0.3$ Kelvin
Higher Acceptance	

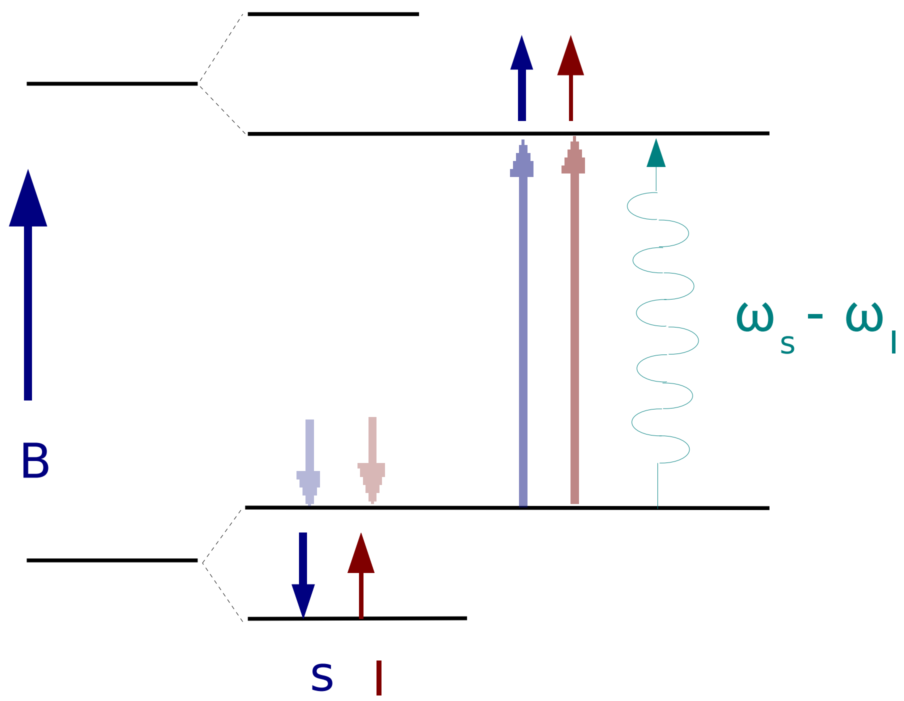
The Solid Effect



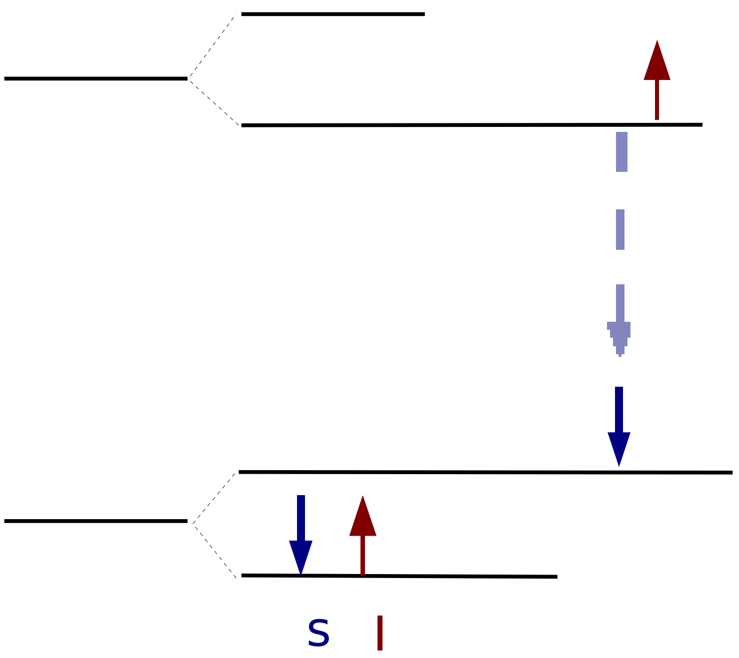
Zeeman energy levels
of a hydrogen-like atom

The lower energy levels are more populated because the electron spins are polarized by high field & low temperature

THE SOLID EFFECT

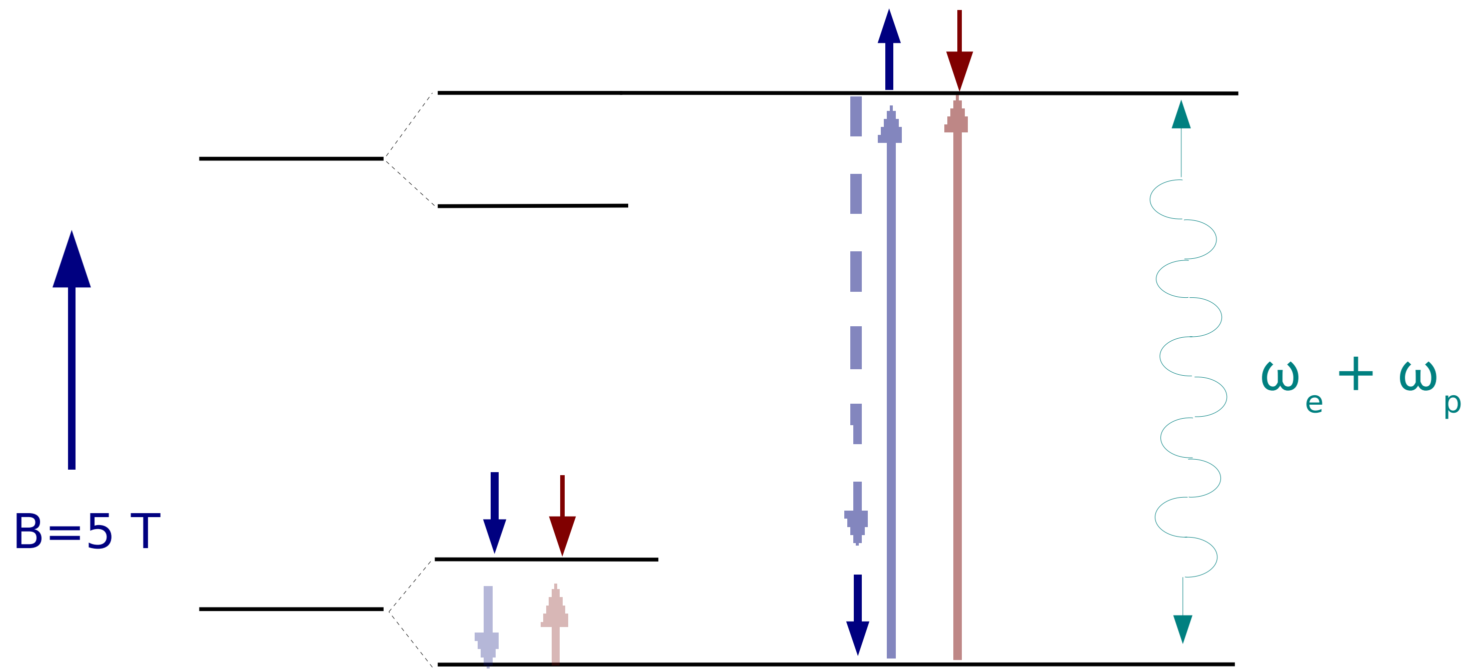


Microwaves drive forbidden transitions that flip both electron & proton spins.



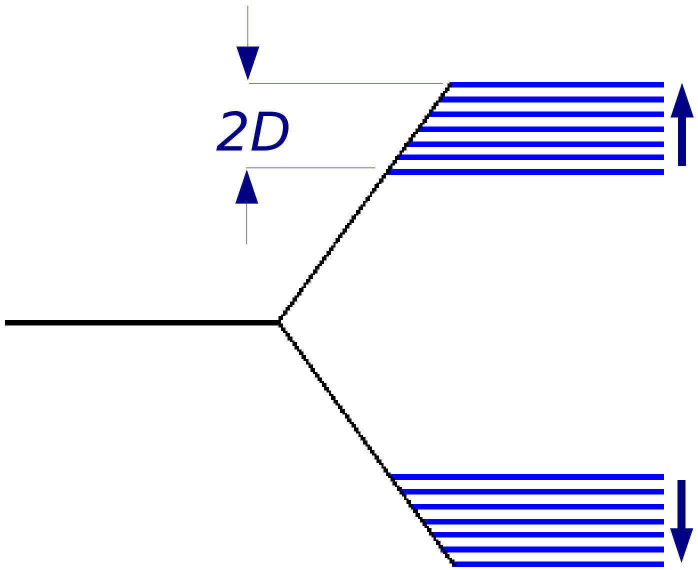
Electrons quickly relax back to Thermal equilibrium (short T_1).
Proton spin stays flipped (long T_1).

THE SOLID EFFECT



Negative proton polarization

The solid effect is effective only when the ESR linewidth *D* is less than the NMR frequency ω_p



In modern target materials, the ESR Linewidth is broadened by
G-factor anisotropy, hyperfine interaction,
Dipole-dipole interactions...

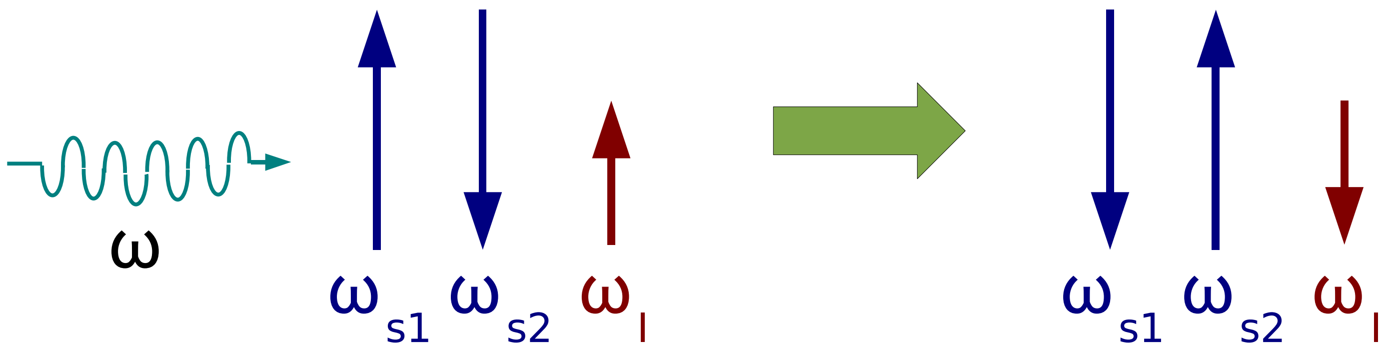
Can't drive one forbidden transition without driving the other at the same time!

Two other spin-transfer mechanisms are effective when $D \geq \omega_p$

Inhomogeneously broadened: Cross effect
Homogeneously broadened: Thermal mixing

The cross effect is effective when *D* is inhomogeneously and electrons are weakly coupled via cross relaxation.

A three-spin process between two electronic and one nuclear spins.



Spin flips satisfy:

$$\omega_{s1} - \omega_{s2} = \omega_I$$

Microwaves on low-freq. side of ESR line drive protons spin-up to spin-down.
→ Negative polarization

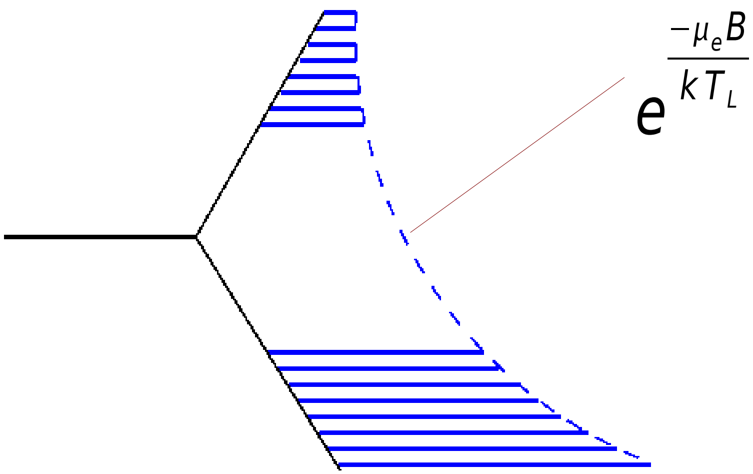
Microwaves on high-freq. side of ESR line drive protons spin-down to spin-up.
→ Positive polarization

Thermal mixing is the dominant spin-transfer mechanism when the density of paramagnetic radicals is high, resulting in substantial dipolar broadening.

Zeeman and dipole-dipole interactions are treated as thermodynamic reservoirs with separate temperatures, T_Z and T_s

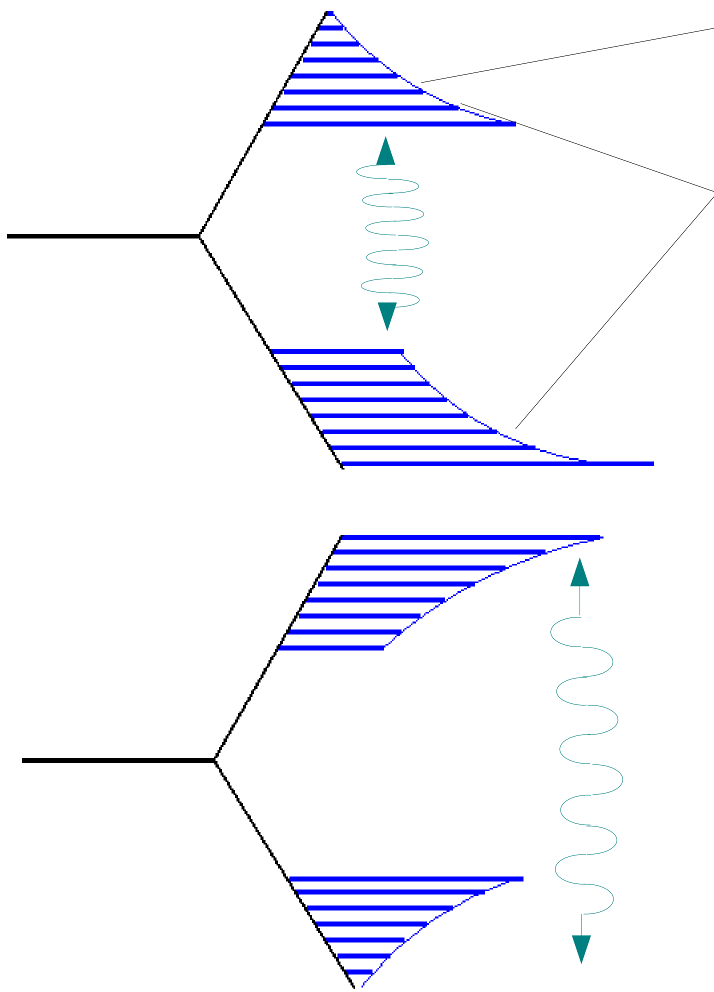
On a time scale determined by T_1 the Zeeman states populate according to a Boltzmann distribution characterized by the temperature of the bulk material, the *lattice temperature* T_L.

Spins in equilibrium with lattice $\longrightarrow$ $P = P_{TE}$



Population of dipolar states also described by lattice temperature

With the application of microwaves near the ESR frequency the dipolar populations redistribute themselves according to a new characteristic temperature, the *dipolar* or *spin temperature* T_s.



Redistribution takes place *fast*
t_2 "spin-spin relaxation time constant"

$$e^{\frac{-E_s}{kT_s}}$$

μ–wave freq. < Larmor freq.
cools the "dipolar reservoir"

$$T_s < T_L$$

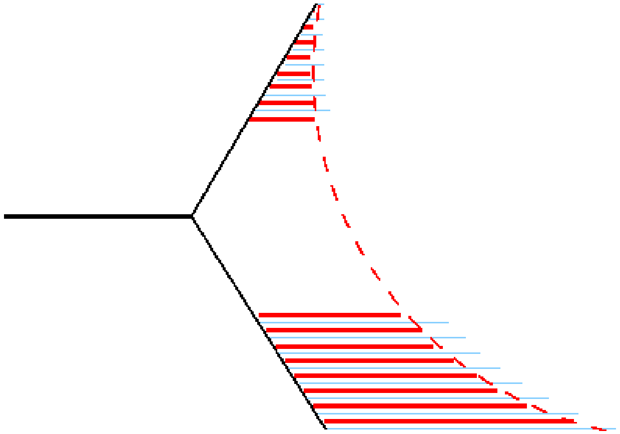
μ-wave freq. > Larmor freq.
heats the "dipolar reservoir"

$$T_s < 0$$

→ *Negative spin temperature*

If ESR width ~ nuclear Zeeman splitting, the dipolar and nuclear Zeeman systems can easily exchange energy with one another (in good “thermal contact”).

The nuclear Zeeman system will cool towards the same spin temperature as the dipolar system!



Equal Spin Temperature (EST)

All nuclear species in the sample will be cooled and polarized to the same spin temperature.

Example, $^{15}NH_3$: P(H) = 94% @ 5T

T_s = 3 mK

P(^{15}N) = 17%

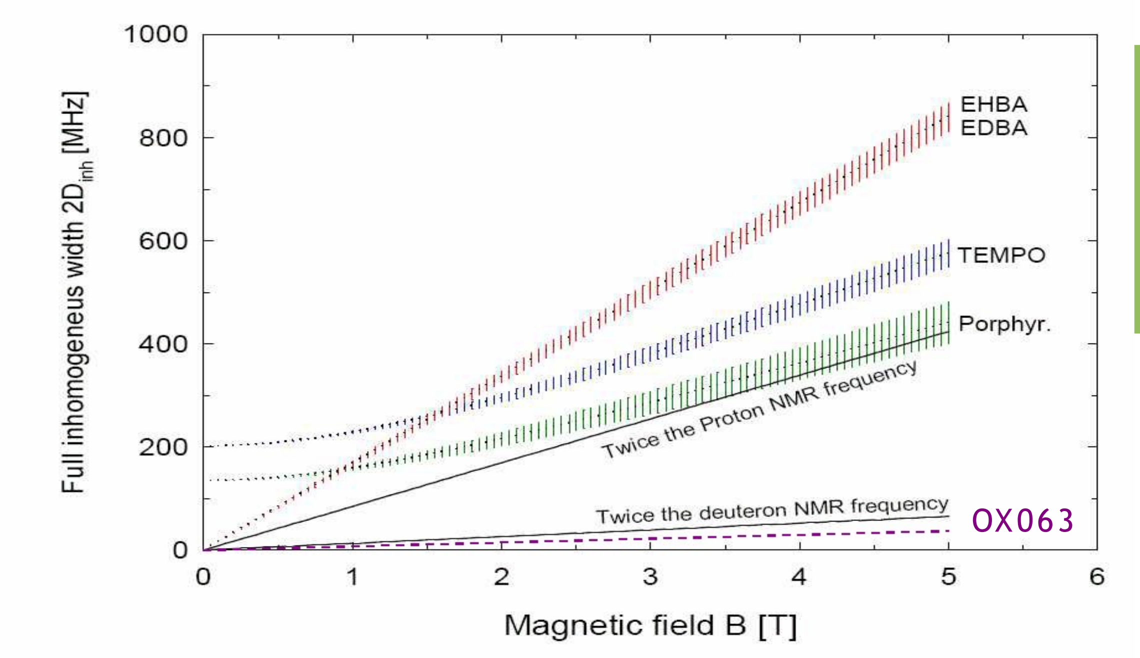
- Borghini model of DNP via *Thermal Mixing* (high temp limit):

$$P_{I,max} = \left(\frac{I+1}{3}\right) \frac{\omega_s}{kT} \frac{\omega_I}{2D}$$

Nuclear Larmor frequency

Width of ESR line

Thermal mixing is most effective when the ESR linewidth is closely matched to the nuclear Larmor frequency.

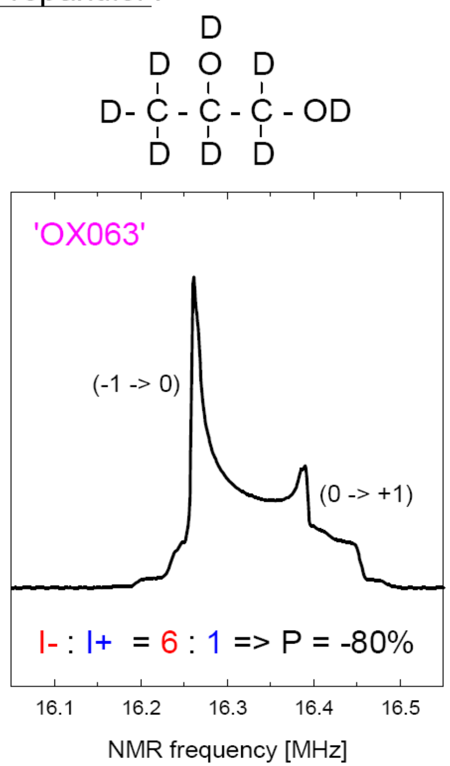


Smaller magnetic moment of the deuteron makes it more difficult to polarize.

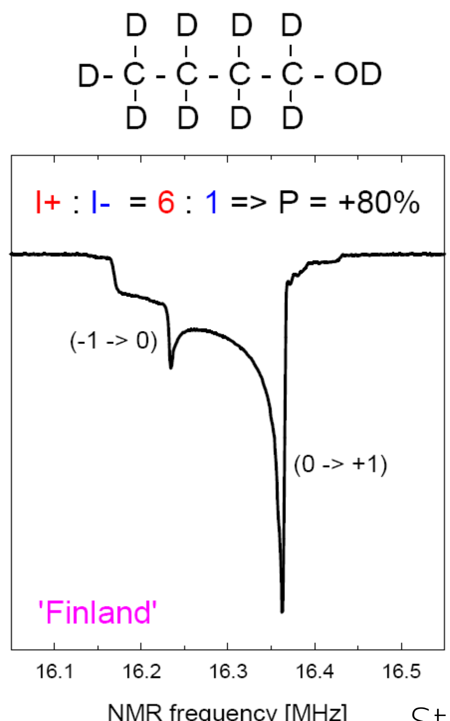
St. Goertz, et al.
NIM A 526 (2004) 43-52

- Recent trityl radicals have **doubled** the maximum polarization of deuterated alcohols:
  - 80% with trityl-doped D-butanol and D-propanediol at 2.5T & 200 mK (Bochum)
  - 87% with trityl-doped D-propanediol at 5T & 200 mK (JLab)

D-Propandiol :



D-Butanol :



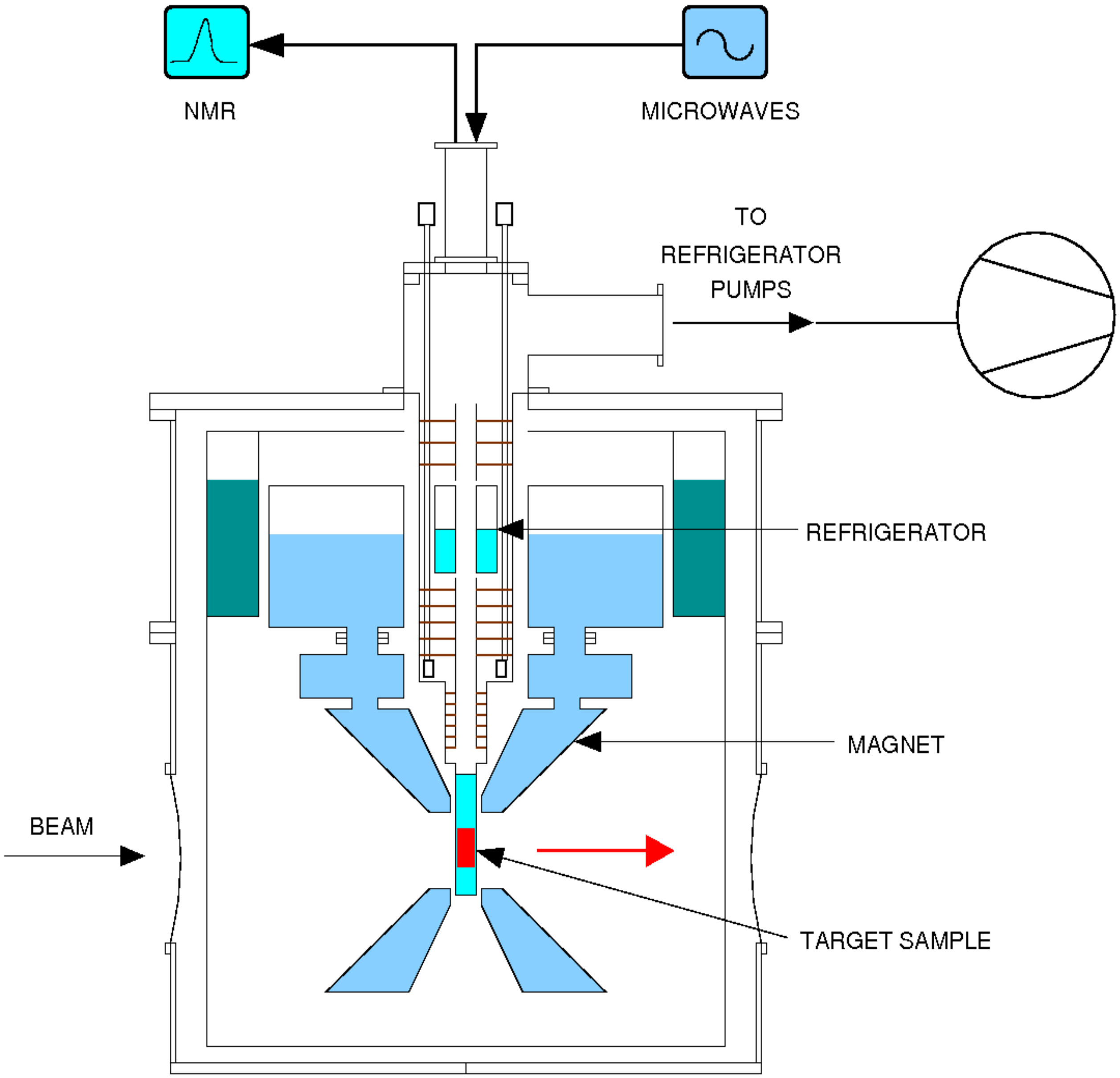
<u>Trityl paramagnetic radicals</u>
developed by Amersham Health for DNP in medical research

'OX063' for polar molecules

'FINLAND' for non-polar molecules

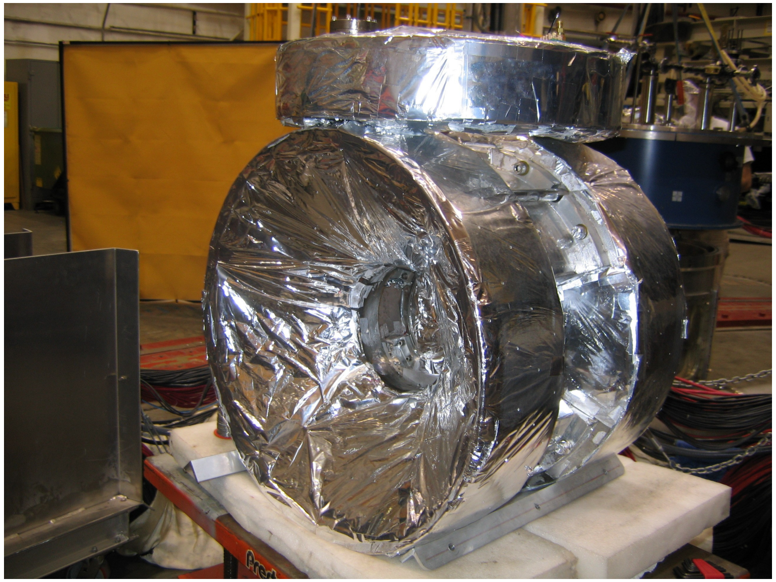
St. Goertz, et al.
NIM A 526 (2004) 43-52

Polarized Target Instrumentation



Magnets

- DNP Requirements: 2 – 5 Tesla ± ~100 ppm
- Other design criteria determined by experimental requirements (field direction, opening angle, etc)



Refrigeration

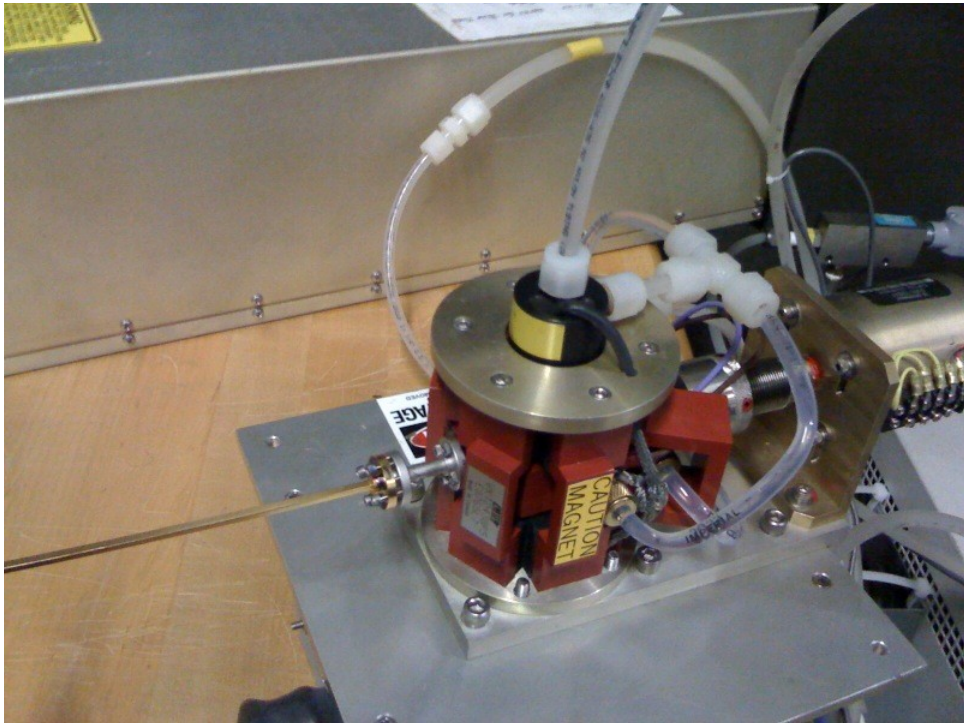
- ^{4}He Evaporation Refrigerator
  - Base Temperature ~ 0.9 K
  - Cooling power up to ~ 1.5 W at 1 K
- ^{3}He Evaporation Refrigerator
  - Base Temperature ~ 0.2 K
  - Cooling power up to ~ 0.5 W at 0.5 K
- ^{3}He-^{4}He Dilution Refrigerator
  - Base Temperature ~ 0.01 K
  - Cooling power up to ~ 0.4 W at 0.3 K

Refrigeration capacity is limited by the pumping rate and efficiency of low-temperature heat exchangers.

MICROWAVES

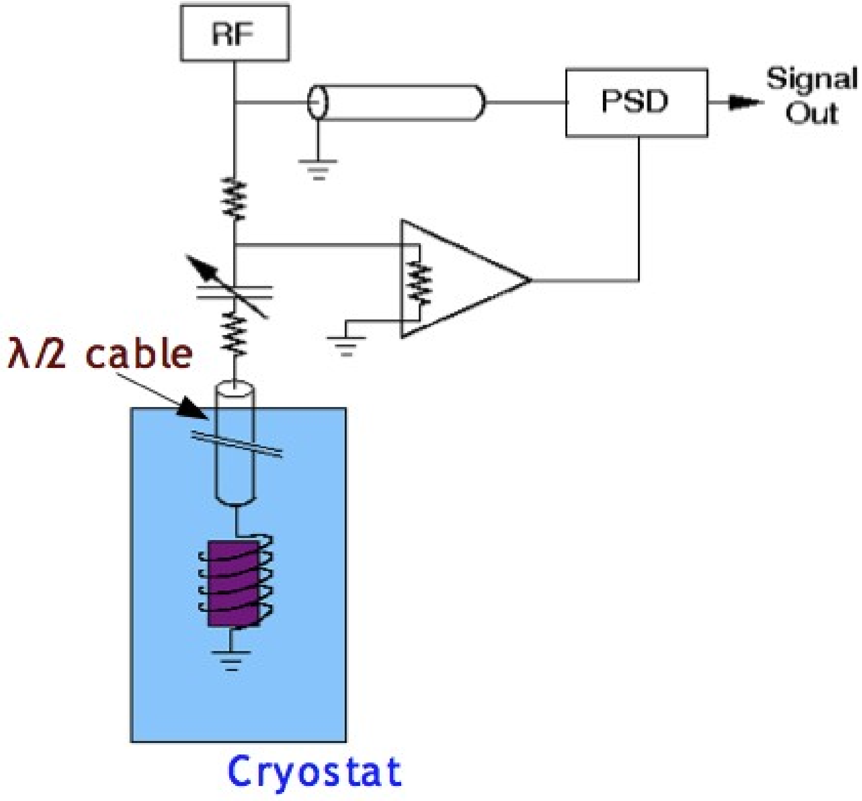
- Requirements: 140 GHz at 5 Tesla, ~ 20 mW/g
  70 GHz at 2.5 Tesla, ~ 2 mW/g

- Sources: Extended Interaction Oscillator, 10 – 20 W
  Klytrons, IMPATT & Gunn diodes, 500 mW



NMR

❖ Continuous-wave NMR using the Liverpool Q-meter for the measuring the polarization of DNP targets has been the *de facto* standard for more than 3 decades



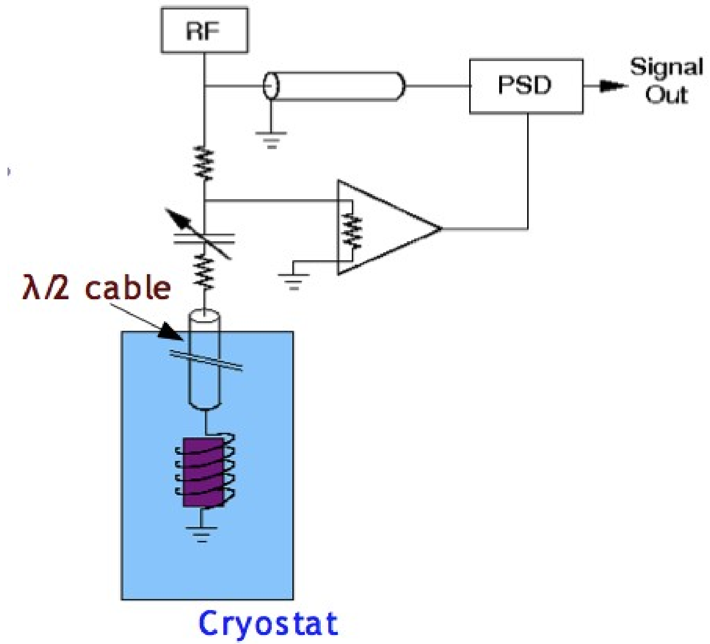
NMR Frequencies (MHz) @ 5T

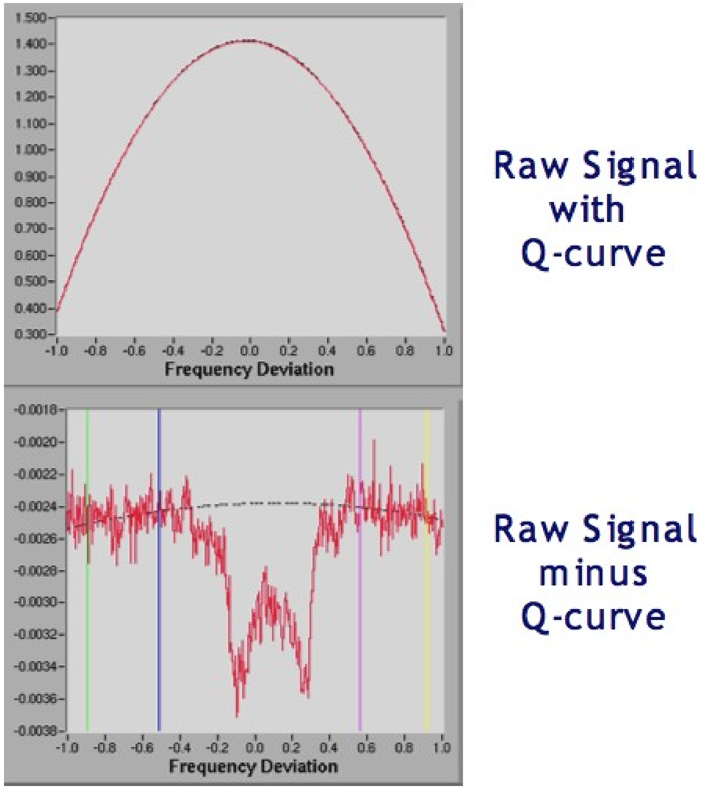
^{1}H (1/2)	213.0
^{2}H (1)	32.7
^{3}He (1/2)	162.3
^{6}Li (1)	31.3
^{7}L (3/2)	81.8
^{13}C (1/2)	55.6
^{15}N(1/2)	21.6 ½

NMR

❖ Polarized NMR signal (~90%) must be calibrated against *Thermal Equilibrium* signal (< 0.5%)

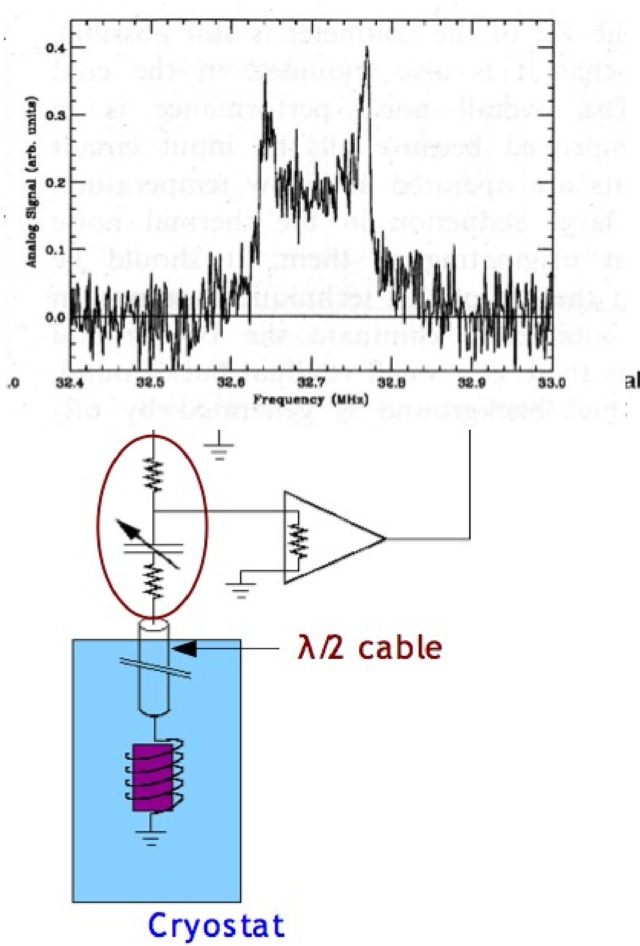
❖ Accuracy of TE signal is limited by signal-to-noise ratio and stability of LCR circuit due to “drift” of resonant λ/2 cable

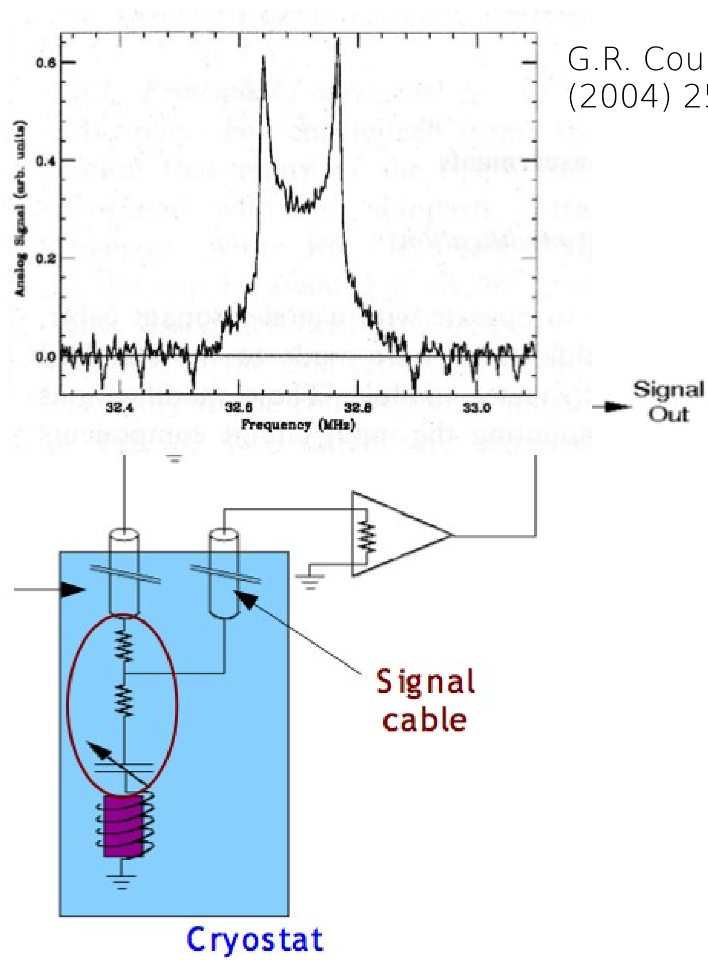




NMR

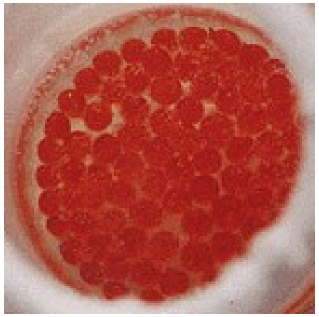
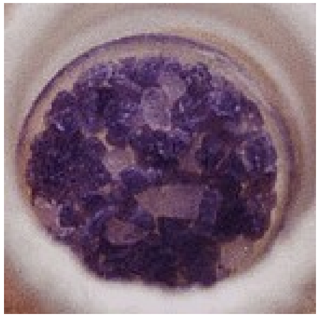
- One solution is to remove the λ/2 cable
  - two cables instead of one
  - tuning LCR circuit more difficult





G.R. Court et al., NIM A 527 (2004) 253

- Successful material for DNP characterized by three measures:
  1. Maximum polarization
  2. Dilution factor
  3. Resistance to ionizing radiation


Material	Butanol	Ammonia, NH_3	Lithium Hydride, ^7LiH
Dopant	Chemical	Irradiation	Irradiation
Dil. Factor (%)	13.5	17.7	25.0
Polarization (%)	90 - 95	90 - 95	90
Material	D-Butanol	D-Ammonia, ND_3	Lithium Deuteride, ^6LiH
Dil. Factor (%)	23.8	30.0	50.0
Polarization (%)	80 - 90	50	55
Rad. Resistance	moderate	high	very high
Comments	*Easy to produce and handle*	*Works well at 5T/1K*	*Slow polarization, long T_1*

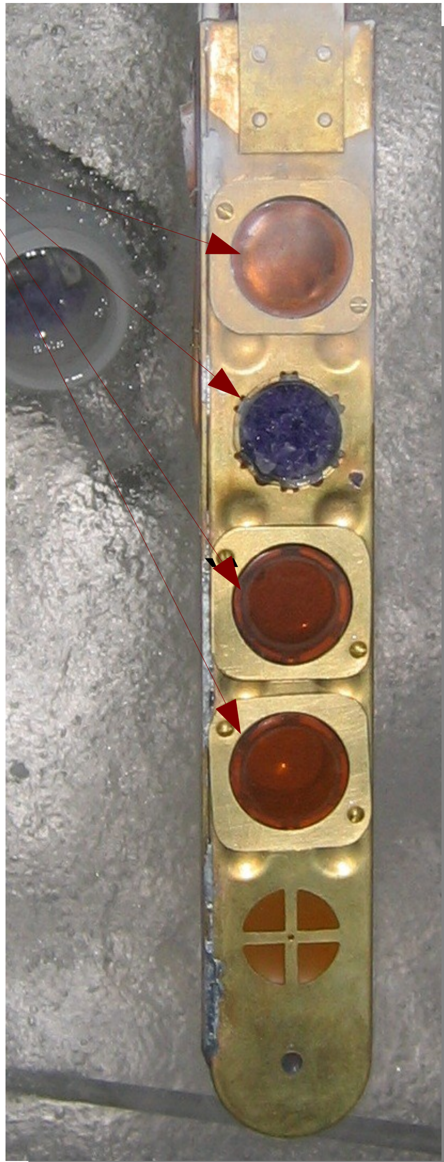
JLab Hall B Polarized Target

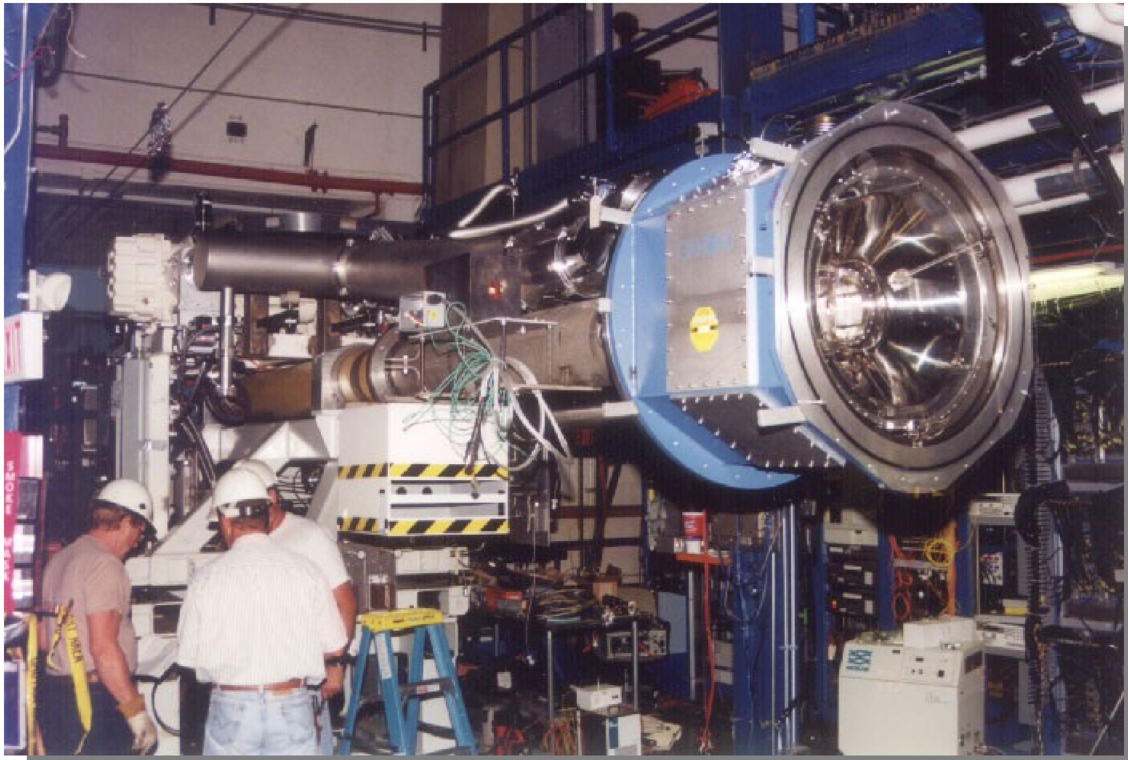
C.D. Keith, et al.
NIM A 501 (2003) 327

Protons (and deuterons) in NH_3 (ND_3) are ***continuously*** polarized at 5 Tesla, 1 Kelvin.

Proton polarization: ~80 - 90%
Deuteron polarization: ~25 – 40%
Luminosity ~ 5×10^{34} cm^{-2} s^{-1}

Multiple samples on target insert

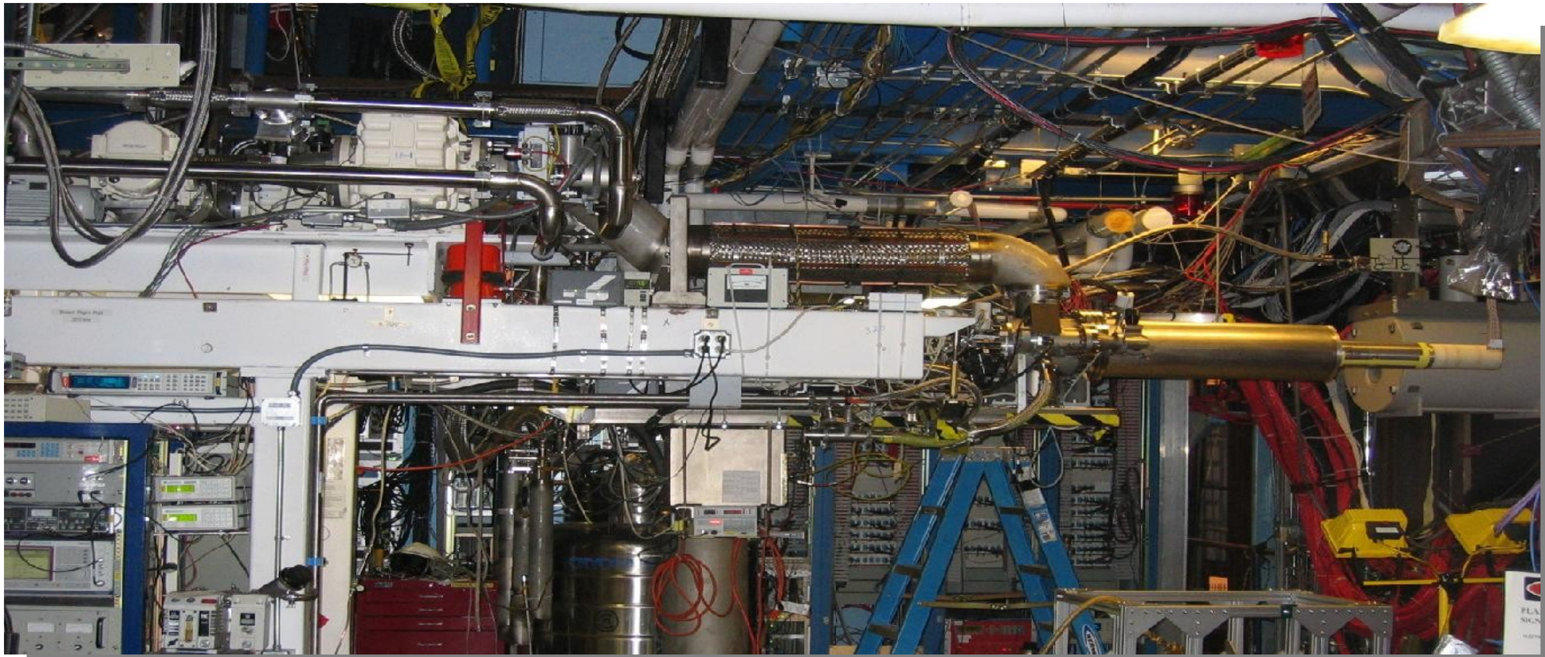




JLab Hall B Frozen Spin Target

C.D. Keith et al.
In preparation

Protons in TEMPO-doped butanol are polarized once per week at 5 Tesla, 0.25 Kelvin.



Polarization:	90% @ 5 T
Temperature:	< 30 mK
Holding Field:	0.54 T longitudinal *or* 0.50T transverse
1/e Relaxation Time:	120 days (+)
	60 days (–)
Luminosity:	$\sim 10^{32}$ cm^{-2} s^{-1}

SUMMARY

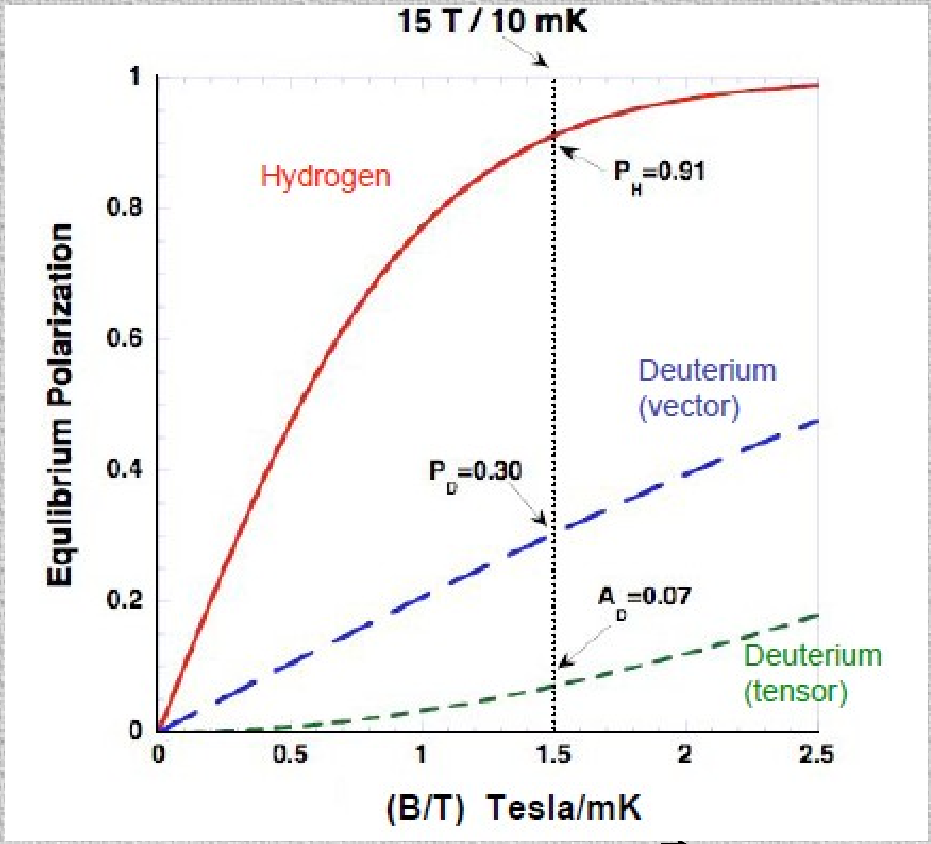
- Solid, Dynamically Polarized Targets are a well-developed, mature field
- DNP can provide highly polarized targets for either high luminosity or high acceptance experiments
- There continues to be steady improvement in the performance and reliability of these targets

    Deuteron polarizations 80 – 90 %
    Frozen Spin Relaxation Times >3000 hrs
    Luminosities exceeding 10^{35} cm^{-2} s^{-1}

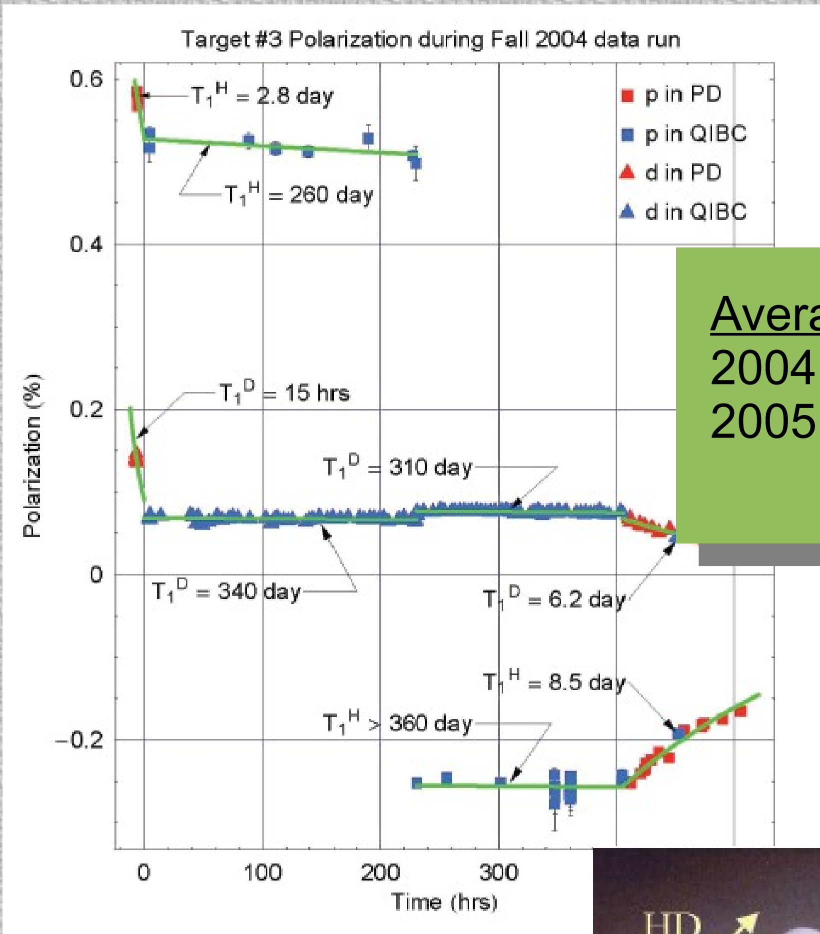
HDICE TARGET: Proposed by Honig (1967)

Development began at Syracuse (1983) and continued at Brookhaven.
Personnel and equipment at JLab since 2007

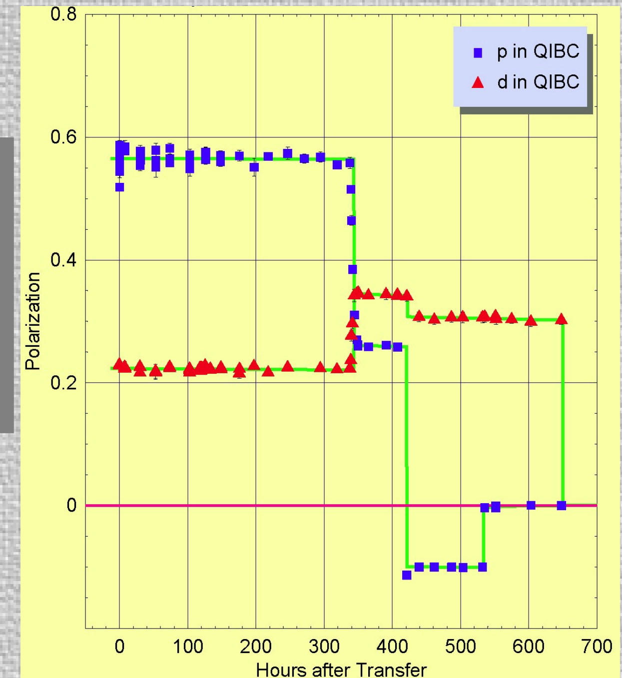
- Prepare purified HD sample with small admixture of o-H_2 & p-D_2 (short T_1)
- Polarize via brute force: ~10mK and 15 T *(P_p=91%, P_d=30%)*
- "Age" sample in order to convert o-H_2→p-H_2 & p-D_2→o-D_2 (long T_1)
- Utilize in beam at 0.3K and 0.9T (Frozen Spin)



$$P = \tanh\left(\frac{\vec{\mu}\cdot\vec{B}}{kT}\right)$$



<u>Average in-beam polarization</u>
2004: proton ≈ +53%, -26%
2005: deuteron ≈ +31% (FAFP)



<u>Target dimensions</u>
Ø13 x 50 mm^2
Aluminum cooling wires
(18% by weight)

<u>Forbidden Adiabatic Fast Passage</u>
Transfer up to 2/3 of proton
polarization to deuteron